

## **Mesoscale Dynamics, Lateral and Vertical Mixing in China Seas and Western Pacific**

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### **LONG TERM GOAL**

The long-term goal of our research program is to understand and parameterize the links between background forcing and ensuing mesoscale and small-scale features of oceanic dynamics, with emphases on lateral and vertical mixing.

### **OBJECTIVES**

The objectives for 2012 were:

- (i) to conduct new measurements of turbulence, stratification, and currents in the South China Sea (SCS) for the purposes of further studies on coupling high-amplitude internal waves and mixing and developing a comprehensive database for the region;
- (ii) to study the variability of internal waves and turbulent kinetic energy (TKE) dissipation rate in the southeastern part of the East China Sea (ECS), particularly in relation to the tidal dynamics in the region;
- (iii) to continue analysis of the distribution of TKE dissipation rate in different areas of SCS and estimate the contributions of pycnocline and BBL to the dissipation on the shelf, and
- (iv) to initiate collaboration with oceanographers of Sri Lanka, helping to shape a framework of the ONR's ASIRI-DRI.

### **APPROACH**

Analysis of field data collected in ECS and SCS during the research cruises of KORDI (Korea) and Xiamen University (China P.R.), with Drs. Jae Hak Lee and Zhiyu Liu as the Chief Scientists. New data were collected in SCS during summer season of 2012.

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## WORK COMPLETED

### *A. Measurements in SCS*

Oceanographers of Xiamen University led by Dr. Zhiyu Liu carried out three cruises this summer, lasting in total one and a half months. Measurements were conducted in estuarine region, on the shelf and in open ocean (i.e. central basin of SCS). The most interesting results were obtained in the outer edge of the Taiwan Shoal in the northeastern SCS. Two weeks of mooring ADCP and CTD-chain data were successfully collected at two sites along the 60-m isobath. At one of these sites, continuous turbulence profiling and echo sounder measurements were conducted for almost 5 days. Internal waves were very active and the region was replete with high-frequency internal wave events. These data allow a comprehensive analysis on the interplay between internal waves and turbulent mixing. In the deeper layer of the SCS, turbulent dissipation rate of less than  $10^{-9}$  W/kg was measured. Thus, the noise level of the MSS-90L profiler used by our Chinese collaborators is definitely below  $10^{-9}$  W/kg, which supports the notion that relatively high dissipation rate in the upper pycnocline of SCS ( $\varepsilon$  was generally above  $10^{-8}$  W/kg) reported in Lozovatsky et al. [2012] was not affected by the profiler noise level. Also, during this summer cruise, 26-hours continuous measurements of turbulence were conducted at a station in the central basin of the northern SCS (i.e. St. OS0). It will help to illustrate temporal variability of the dissipation rate at a fixed (drifting) station in comparison with spatial variability analyzed and reported in Liu and Lozovatsky [2012].

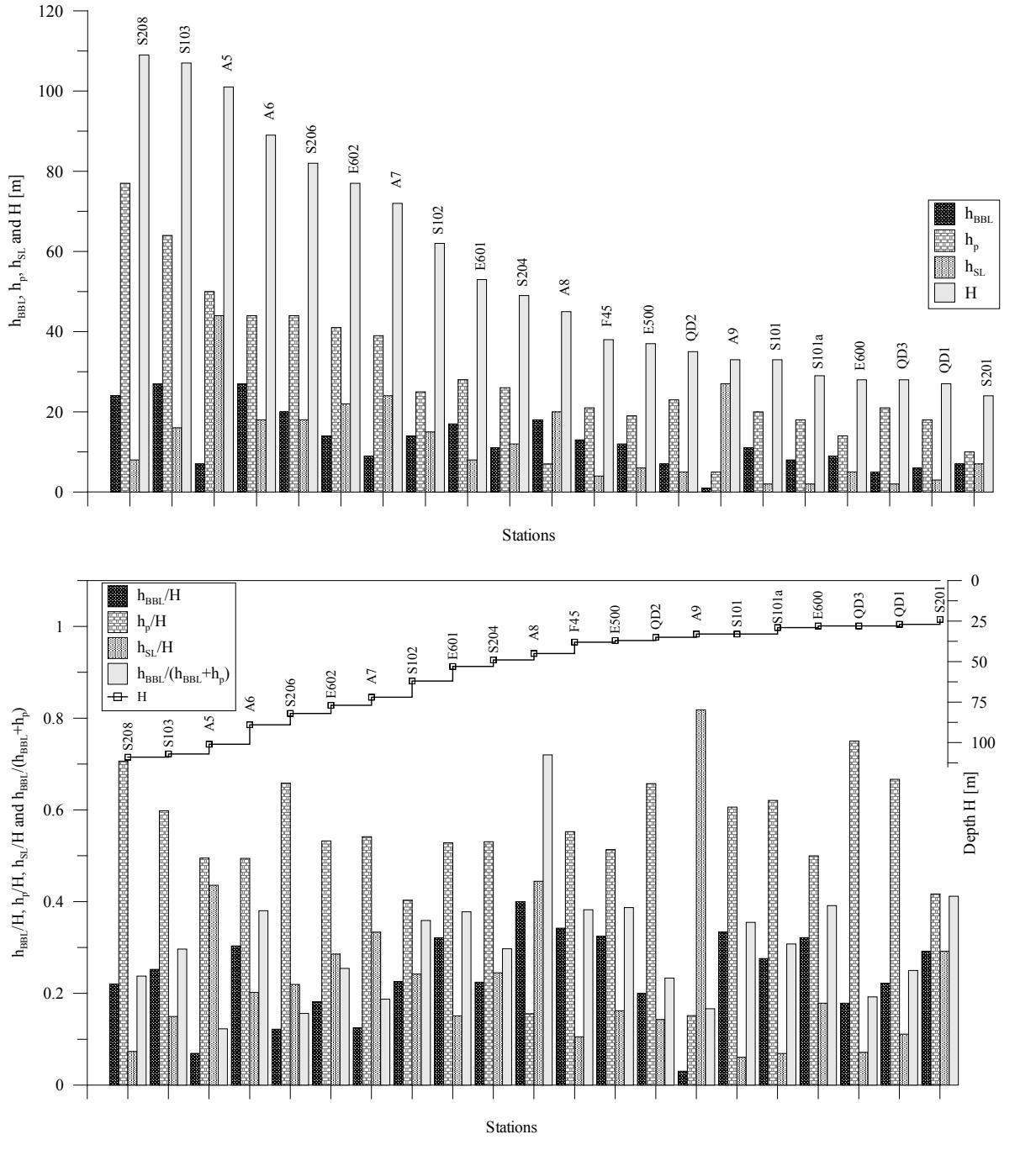
### *B. Analysis of the TKE dissipation rate in the Northern SCS*

It was reported [Lozovatsky and Fernando 2011] that the averaged dissipation rates  $\langle \varepsilon_p \rangle$  in the upper pycnocline of the northern SCS compares well with the MacKinnon and Gregg [2003] parameterization as well as local Richardson numbers. The energy dissipation in internal waves that propagate across the deep SCS basin west-northwest from the Luzon Strait has regional asymmetry of the latitudinal distribution of  $\varepsilon$ . On the average,  $\langle \varepsilon_p \rangle$  to the north of  $20^{\circ}\text{N}$  is about two times larger than to the south of this latitude. The results were published in Liu and Lozovatsky [2012]. Below we present additional analysis of shelf turbulence in SCS; detailed results on the spatial variability and parameterization of  $\langle \varepsilon_p \rangle$  have been submitted for publication in JGR [Lozovatsky et al. 2012].

## RESULTS

The dissipation rate  $\varepsilon(z)$  was measured at 10 stations in the northern SCS between  $20^{\circ}\text{N}$  and  $22^{\circ}\text{N}$  and between  $112^{\circ}\text{E}$  and  $116^{\circ}\text{E}$  on the eastern shelf of China using an MSS-60 microstructure profiler during 2009 research cruises of XMU.

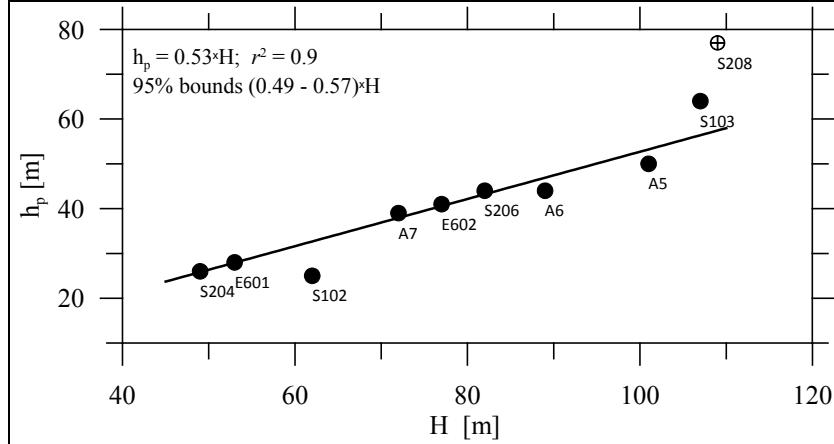
The relative contributions of three major layers to the depth-integrated dissipation on the shelf, the thicknesses of bottom layer (BBL), pycnocline and surface layer (SL) as well as the fractions of the entire water column occupied by these layers are shown in Fig. 1.



**Figure 1.** The thicknesses of the BBL, pycnocline, and SL on the shelf (a) and the fractions of the water column (b) occupied by these layers (bars). The station names are given above the stepped line that shows the depth  $H$  of the seafloor (right axis). The data in the plot are arranged from the deeper to shallower stations.

The characteristic height of BBL appears to be about 10 m (max  $h_{BBL} = 27$  m); the mean and median depths of SL are 14 and 8 m (max  $h_{SL} = 44$  m); and the corresponding numbers for the thickness of the pycnocline  $h_p$  are 29 and 22 m. The fractions of the water column occupied by BBL, pycnocline, and

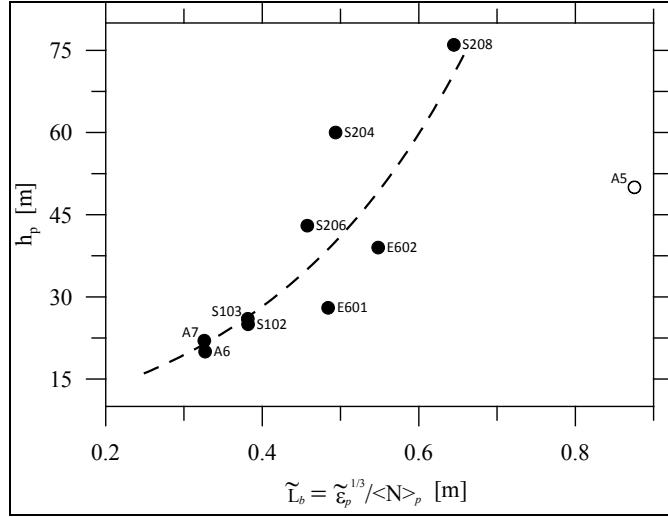
SL (Fig. 1b), on the average, are 0.23, 0.53, and 0.24, respectively. The variation coefficient (rms/mean) is smallest (0.28) for the ratio  $h_p/H$ ; larger (0.43) for  $h_{BBL}/H$ ; and the largest (0.76) for  $h_{SL}/H$ . The latter reflects the fact that the depth of SL across the shelf is constantly affected by variable sea-surface fluxes but not the water depth. On the shelf, the pycnocline thickness  $h_p$  is reasonably well ( $r^2 = 0.9$ ), correlated with the water depth  $H$  (see Fig. 2).



**Fig. 2. The pycnocline thickness  $h_p$  vs. the seafloor depth  $H$  for ten shelf stations with  $H > 50$  m and  $h_p > 20$  m. A linear regression with the 95% confidence bounds and the coefficient of determination  $r^2$  are given in the plot, not accounting for St. 208, which appears to be an anomaly.**

This is not the case for  $h_{BBL}$  and more so for  $h_{SL}$ . Although a linear regression of  $h_p$  vs.  $H$  holds for the complete set of shelf stations (with slightly different regression coefficient (0.55) and a lower  $r^2 = 0.86$ ), we have limited our further analysis to 10 relatively deep stations ( $H > 50$  m) with a fairly wide pycnocline ( $h_p > 18$  m) to ensure statistical reliability of integrated estimates of  $\hat{\varepsilon}$  and other variables in BBL and pycnocline. The samples from these stations are shown in Fig. 2. The observed correspondence between  $h_p$  and  $H$  could be linked to smaller phase speeds and group velocities of high-amplitude IW in shallower waters compared to the deep ocean. The lower energy density in the stratified interior reduces the potential for turbulence and mixing that is responsible for widening of the pycnocline.

The positive correlation between the pycnocline thickness and the characteristic bulk buoyancy scale  $\tilde{L}_b = \tilde{\varepsilon}_p^{1/3} / \langle N \rangle_p$  (Fig. 3) supports the assumption that  $h_p$  is predominantly influenced by internal mixing in the pycnocline rather than by turbulence in the surrounding boundary layers.

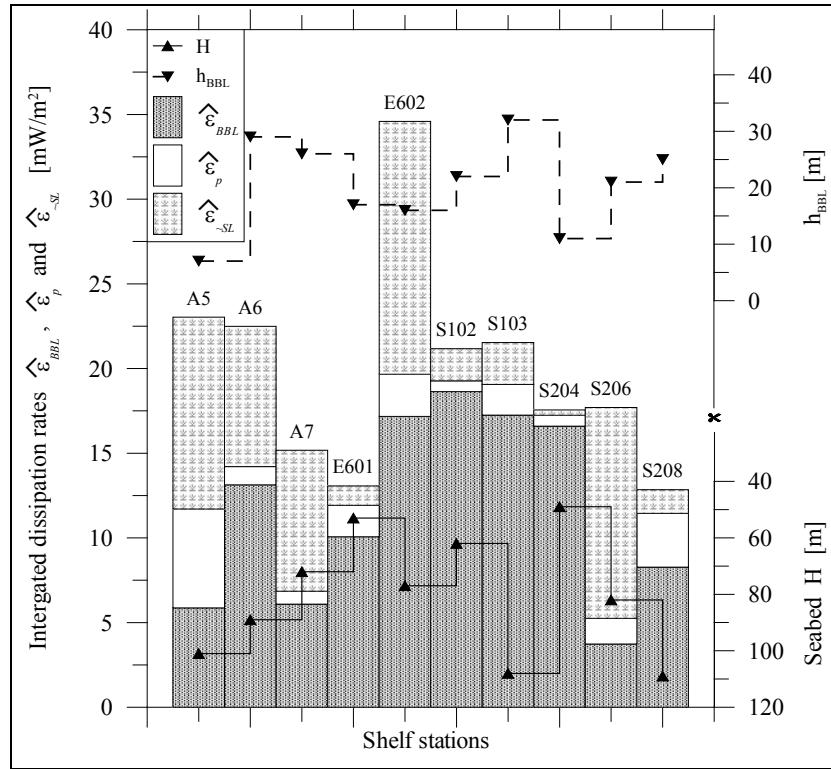


**Fig. 3. The pycnocline thickness  $h_p$  vs. the bulk buoyancy scale  $\tilde{L}_b$  at selected shelf stations. The dashed line is a least squared approximation of all samples excluding A5.**

Here  $\tilde{\varepsilon}_p = \hat{\varepsilon}_p / \rho$ . In nine out of ten shelf stations,  $h_p$  shows a growing trend with  $\tilde{L}_b$ . It appears that at St. A5 the pycnocline was eroded by strong wind-induced mixing that caused deepening of SL to more than 40 m, therefore reducing  $h_p$ . Simultaneously, an elevated dissipation rate was registered in the pycnocline at A5, presumably generated by a solitary internal wave. Similar short-lived increase of  $\varepsilon_p$  (by an order of magnitude), directly associated with the propagation of a solitary-like wave in the pycnocline of the East China Sea, has been reported in Liu et al. [2009], where the event was captured by concurrent microstructure and ADCP measurements.

The estimates of dissipation rate integrated over the thickness of SL  $\hat{\varepsilon}_{SL}$ , pycnocline  $\hat{\varepsilon}_p$ , and BBL  $\hat{\varepsilon}_{BBL}$  at selected shelf stations are shown in Fig. 4 (stacked bars), along with the ocean depth and BBL thickness. Note that  $\hat{\varepsilon}_{SL}$  is overwhelmingly affected by wind mixing, varying from  $\sim 0.3$  mW/m<sup>2</sup> (S204) to 14.9 mW/m<sup>2</sup> (E602). The fraction of the dissipation in SL (excluding upper 5 m) is as low as 9% and as high as 70% of that over the entire water column. Our focus, however, is on the pycnocline and BBL, while  $\hat{\varepsilon}_{SL}$  is presented here only for completeness.

As shown in Fig. 4,  $\hat{\varepsilon}_{BBL}$  on the shelf dominates that over the pycnocline  $\hat{\varepsilon}_p$ . The absolute values of  $\hat{\varepsilon}_{BBL}$  vary from 3.7 (S206) to 18.7 (S102) mW/m<sup>2</sup>. Except at St. A5,  $\hat{\varepsilon}_{BBL}$  takes more than 70% of the combined dissipation ( $\hat{\varepsilon}_{BBL} + \hat{\varepsilon}_p$ ), but often it is close to 90%.



**Fig. 4. The integrated dissipation rate at shelf stations (A5, ... S208) in the pycnocline  $\hat{\varepsilon}_p$  and SL  $\hat{\varepsilon}_{-SL}$  (excluding upper 5 m). They are stacked over the integrated dissipation in BBL  $\hat{\varepsilon}_{BBL}$ . A combined height of the three bars at every station gives the total integrated dissipation of the water column below  $z = 5$  m. The depth of the seabed  $H$  and the height of BBL  $h_{BBL}$  are also shown in the plot.**

Only at St. A5,  $\hat{\varepsilon}_{BBL}$  is equal to  $\hat{\varepsilon}_p$  because of an unusual stratification conditions. It has very deep SL ( $h_{SL} = 44$  m), very shallow BBL ( $h_{BBL} = 7$  m) and a wide, highly turbulent pycnocline ( $h_p = 50$  m). Among all shelf stations, the mean dissipation in the pycnocline at A5 may have coincided with a turbulent event akin to the propagation of a solitary wave or a packet of NLIW generated at the shelf break in close proximity to A5. Although  $\hat{\varepsilon}_{BBL}$  is the major contributor to the depth-integrated dissipation on the shelf away from the shelf break, it appears that baroclinic motions, such as internal tidal waves, have only little influence on  $\hat{\varepsilon}_{BBL}$ , given that  $\hat{\varepsilon}_{BBL}$  is generally consistent with the dissipation estimates for barotropic tide.

The magnitude  $V_{td}$  of tidal currents near the seafloor on the shelf varies between  $\sim 0.05 - 0.10$  and  $0.15 - 0.2$  m/s based on our ADCP data at  $\sim 7 - 10$  meters above the bottom. The usual parameterization for the tidal dissipation in BBL,  $\varepsilon_{td} \sim \rho C_D |V_{td}| V_{td}^2$ , where the drag coefficient  $C_D = 2.5 \times 10^{-3}$  (which may vary during the tidal cycle; *Lozovatsky et al.*, 2008 b), could be as low as  $0.3 - 2.5$  mW/m $^2$  and as high as  $9 - 20$  mW/m $^2$ ;  $\hat{\varepsilon}_{BBL} = 3.7 - 18.7$  mW/m $^2$  predicts values well inside this range (see Fig. 4). The integrated dissipation rate in the lower 10 m of the water column at the shelf break ( $H = 160$  m) to the north of our stations has been estimated as  $25$  mW/m $^2$  [St. Laurent, 2008]. By comparing this number

with  $\varepsilon_{td}$  calculated for an assumed  $V_{td} = 0.1$  m/s, St. Laurent [2008] inferred that the observed high dissipation is related to baroclinic energy. We note, however, that  $\varepsilon_{td} \sim V_{td}^3$ , and  $V_{td}$  can easily go up to 0.2 m/s or above [e.g., Souza and Howarth, 2005; Lozovatsky et al., 2010]. Thus the high level of integrated dissipation can be explained by pure bottom drag of barotropic flow. The calculation of available potential energy (APE) of internal waves by Liu and Lozovatsky [2012], however, suggests that baroclinic activity was prevalent at the measurement site. The dominant fraction of the tidal energy on SCS shelf dissipated in a layer of 10 - 30 m height of BBL, where  $\hat{\varepsilon}_{BBL}$  was as high as 17-19 mW/m<sup>2</sup>. The episodic dissipation rate enhancements can be associated with other processes such as solitary waves generated at the shelf brake.

## IMPACT/APPLICATION

Our research program involves collaboration between the US, Chinese and Korean scientists as well as other international groups. One paper on the study of turbulence in SCS has been published in Chinese Science Bulletin and the other is under revision in Journal of Geophysical Research. Dr. Zhiyu Liu (China) visited University of Notre Dame in February 2012 to conduct joint work with PIs. We started new collaboration with oceanographers of National Aquatic Resources Research and Development Agency (NARA) of Sri Lanka, where PI I. Lozovatsky gave a series of lectures on small-scale ocean dynamics (theory, instrumentation, and observations) in April 2012. This helped capacity building and planning for a joint measurement program in Sri Lanka waters, which is of interest for ONR's ASIRI DRI.

## TRANSITIONS

None

## RELATED PROJECTS

The Co-P.I. Fernando is the PI of another ONR-PO funded project dealing with air-sea interactions in the Bay of Bengal during Indian Ocean Monsoons.

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